Determination of forced convection heat transfer coefficients and development of empirical correlations for milk in vessel with mechanical agitators

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Abstract Heating of milk is an important unit operation to produce many milk based products. This process is done either in heat exchangers or in agitated vessels, where the mode and type of heat transfer plays a significant role. Use of mechanical agitator with suitable impeller would result in uniform agitation of the liquid. Data for forced convection heat transfer coefficients for milk in agitated vessel have not been documented. In the present investigation, forced convection heat transfer coefficients for milk, using mechanical agitators in vessels have been determined. Experiments have been conducted in vessels (Baffled as well as Unbaffled vessel) that were designed and fabricated under standard procedure employing: (1) Flat Six Blade

Turbine impeller, (2) Inclined Six Blade Turbine impeller, (3) Three Blade Propeller impeller and (4) Two Bladed Paddle. Heat transfer coefficients were determined for ($\bar{h}$) for cow milk (3.5% fat), standardised milk (4.5% fat) and full cream milk (6.0% fat). The Two Bladed Paddle was found to as yield the highest heat transfer coefficient ($\bar{h}$) for all three types of milk. In addition, empirical correlations for the forced convection heat transfer using $Nu = a \cdot Re^b \cdot Pr^{0.33}$ have been developed for each case. These heat transfer correlations derived will find application in large scale design and the experimental setup would be useful for future investigation with different liquids and impellers.

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List of symbols

A	Heat transfer area (m^2)
m	Mass of milk (kg)
$\bar{h}$	Forced convection heat transfer coefficient $\left(\frac{W}{m^2 K}\right)$
T_s	Vessel bottom surface temperature (K)
T_m	Temperature of milk (K)
T_B	Bulk mean temperature of milk (K)
T_{mo}	Initial temperature of milk (K)
T_{mf}	Final temperature of milk (K)
t	Time (s)
C_{pm}	Heat capacity of milk $\left(\frac{J}{kg K}\right)$
ρ_m	Density of milk $\left(\frac{kg}{m^3}\right)$
μ_m	Viscosity of milk $\left(\frac{kg}{m s}\right)$
k_m	Thermal conductivity of milk $\left(\frac{W}{m K}\right)$

N	Impeller speed (rpm)
D_t	Diameter of milk vessel (mm)
D_a	Diameter of impeller (mm)
Nu	Nusselt number $\left(\frac{hD_t}{k_m}\right)$
Re	Reynolds number $\left(\frac{ND_a}{\mu}\right) \left(\frac{D_a^2 \rho}{\mu}\right)$
Pr	Prandtl number $\left(\frac{C_{pm} \mu_m}{k_m}\right)$
X_F	Fat fraction in milk
X_w	Water fraction in milk
a, b, n	Correlation constants in $Nu = a \cdot Re^b \cdot Pr^n$
SNF	Solid non-fat
FBT	Flat Six Blade Turbine impeller
IBT	Inclined Six Blade Turbine impeller

Introduction

Milk is a nutritive drink containing fat, protein, sugars, minerals and water. Milk production in India according to 2015–16 statistics is 155.5 million tonnes (National Dairy Development Board 2016). Out of the entire milk produced, 47% is utilised for milk based sweets (Sharma 2006). An empirical correlation in milk processing to make khoa has been reported by Kumar (1985). In many processing operations, milk is boiled by using direct flame or by steam. This is a two-stage process namely, (1) Pre-heating the milk to boiling condition and (2) Boiling the milk to concentrated forms for example in khoa making (Choudary et al. 2017). Hence heat transfer studies in milk are significant from the point of view of optimum energy utilization and to prevent secondary reactions while heating. Kumar et al. (2011, 2013) have reported natural convection heat transfer between hot milk and air. They have also reported pool boiling heat transfer coefficients for different heat inputs, while the milk was manually stirred and boiled. Heat transfer coefficient values for milk in pool boiling has been also reported by Babu et al. (2016). An exhaustive list of studies and correlations were reported for many other liquids, using different impellers (Mohan 1992). It is understood that mechanical agitators using suitable impeller is a desirable method as it would result in uniform agitation of liquid. To attain uniform mixing, paddle agitators of different designs was modelled and analysed (Rajasekaran and Kumar 2014). However, forced convection heat transfer studies for milk in vessels using mechanical agitators are not reported in literature. If hot milk is available, it can be sent through pipelines to different operations. One way to produce hot milk is to keep it at desired hot temperature in agitated vessels. From the vessel, the hot milk can be pumped through pipelines. The present experimental investigation aims at (1) Determination of forced convection heat transfer coefficient using

standard impellers of different types and identification of the impeller providing better $\bar{h}$ value for cow milk (fat 3.5%), standardised milk (fat 4.5%) and full cream milk (fat 6.0%). (2) Development of empirical correlations of the form $Nu = a \cdot Re^b \cdot Pr^{0.33}$. It is to be noted in all these correlations (Pr^n) is kept at $Pr^{0.33}$ (Karez et al. 1958; Mohan et al. 1992; Debab et al. 2011).

In the present investigation the type of agitator that would give highest $\bar{h}$ for three types of milk has been identified. In addition, empirical correlations for the forced convection heat transfer for milk have been developed. The experimental setup designed and fabricated provides the means to directly determine forced convection heat transfer coefficients also for liquids other than milk in agitated vessels.

Materials and methods

Raw materials

Popular brand of cow milk, standardised milk and full cream milk procured from Tamil Nadu Cooperative Milk Producers Federation, Chennai were used in the investigation. For each experiment one kilogram of milk was used. The composition of the sample milk is given below.

- (1) Cow Milk Fat (3.5%), SNF (8.5%) and Water (88.0%).
- (2) Standardised Milk Fat (4.5%), SNF (8.6%) and Water (86.9%).
- (3) Full Cream Milk Fat (6.0%), SNF (9.04%) and Water (84.96%).

Experimental setup

The experimental setup used for the present investigation (Fig. 1) was designed and fabricated specifically for the purpose. The vessel geometry and impellers were designed as per the standard procedure described by McCabe (2005), and Geankoplis (2008).

The components of the experimental setup are as follows

Water bath The setup consists of a rectangular cuboid as water bath with a provision to mount the milk vessel on it and with a spout to fill water and a drain at the bottom. Heater is provided inside the water bath. To stabilize the water bath temperature throughout the experiments a thermocouple inside the water bath senses the heat and sends the electrical signal to the temperature controller which displays the bath temperature. The water bath

Fig. 1 Experimental setup for determination of forced convection heat transfer coefficient in milk

temperature can be set at required value by a rotary switch and push button arrangement. The closed loop electronic circuitry controls the heating element so that the set value of temperature is stabilized and maintained at $90 \pm 1^{\circ}\text{C}$.

Milk vessels Two milk vessels viz. Baffled and Unbaffled were used in the experiments. The vessel is mounted on top of the water bath, so that circular bottom surface of the vessel is in contact with water in the water bath. The milk temperature is measured by a second thermocouple mounted in the centre of the vessel. The temperature of milk sensed by the thermocouple is indicated on the display panel in degree Celsius. The milk containing vessel is insulated properly on the outer periphery so that heat is transferred only from the circular bottom surface to the bulk of the milk. The vessel is closed at the top to prevent evaporation.

Agitator assembly Agitation of milk is done by an impeller attached to the agitator shaft which in turn is connected to a DC motor. An encoder disc with 60 slots is mounted on the motor shaft. The disc is made to rotate between the emitter and detector of the IRED optical sensor. As the agitator shaft revolves, speed of rotation is sensed by the encoder and the optical signal is converted to electrical signal and is indicated as rpm on the display panel. The rpm of the rotor can be controlled for values set through the potentiometer provided with the display panel.

Control panel The control panel shows temperature of milk (T_m), rpm of the rotor (set at desired value) and temperature of water bath (T_s) (set at desired value).

Impellers, shaft assembly and scraper

Four types of commonly used impellers for agitated vessels viz Flat Six Blade Turbine (FBT), Inclined six Blade Turbine (IBT), Three Blade Propeller and Two Bladed Paddle were fabricated. Suitable shaft assemblies were also fabricated to mount the impellers (Fig. 2) These were fabricated following standard design procedure (McCabe 2005; Geankoplis 2008).

FBT impeller is widely used in agitated vessels. This impeller generates radial flow currents. The IBT impeller that has been designed and used in this experiment has inclined blades (45° inclination) fixed on a flat circular disc, and this generates angular flow currents. The propeller impeller is an axial flow impeller. All these impellers are designed with a $D_a : D_t$ ratio 0.3:1. To avoid churning during the experiments the speed of FBT, IBT and Propeller Impellers were restricted to 85–150 rpm for Baffled vessel and 50–80 rpm for Unbaffled vessel (with scraper).

A paddle agitator design with surface scraping provision is generally known as anchor agitator. In our experiments Two Bladed Paddle is designed with a $D_a : D_t$ ratio 0.8:1. The rotational speed is kept between 50 and 80 rpm for Baffled vessel. Paddles are generally low speed agitators, as it would cause vortex at high rpm due to large tangential currents.

To investigate the effect of surface wiping (internal) of the vessel on heat transfer coefficient ($\bar{h}$), agitator assembly with scraper was used, exclusively in Unbaffled vessel along with all other type of impellers, except paddle agitator.

Fig. 2 Impellers, Scraper and Shaft Assembly

Experimental procedure

Distilled water was poured into the water bath to the required level of 70 mm to surround the bottom of the milk vessel. The temperature of water bath was maintained at 90 °C throughout the study.

One kilogram of milk was poured into the vessel and stirred with the help of agitator fitted with a specific impeller one at a time for each experiment. The rpm was sensed and regulated by the optical encoder and potentiometer respectively and was displayed in the control panel.

In Baffled vessel, speeds for FBT impeller, IBT impeller and Propeller impeller were varied from 85 to 150 rpm. However, for paddle agitator the speed was set at 50–80 rpm. In Unbaffled vessel, scraper was used along with FBT, IBT and Propeller impeller with speeds varying from 50 to 80 rpm only.

Heat was transferred to the entire milk from the bottom surface of the vessel by forced convection due to agitation. The rise in milk temperature with respect to time was sensed by the thermocouple kept in the milk and was displayed in the control panel in degree Celsius. Thus, time vs milk temperature (T_m) was recorded at regular intervals (5 min).

It was observed that the milk temperature (T_m) varied from 30 to 80 °C for a constant vessel base temperature of

90 °C. Physical properties namely density (ρ_m), viscosity (μ_m), specific heat (C_{pm}), and thermal conductivity (k_m) required to evaluate Nusselt Number, Reynolds Number and Prandtl Number were determined at Bulk mean temperature $T_B = 55^\circ\text{C}$ for all impellers in Baffled and Unbaffled vessels.

Mathematical modelling and determination of heat transfer coefficient ($\bar{h}$)

Heat energy is transferred from the vessel bottom to the bulk of milk that is being agitated. Thus, the expression for heat balance equation is given as

Rate of heat transfer by convection
= Rate of heat accumulation in milk

$$\bar{h} \cdot A(T_s - T_m) = \frac{d}{dt}(m C_{pm} T_m) \quad (1)$$

This equation can be integrated resulting in

$$\left(\frac{\bar{h}A}{m C_{pm}} \right) t = -\ln(T_s - T_m) + C_1 \quad (2)$$

The integration constant C_1 can be evaluated using initial condition that at

$$t = 0, \quad T_m = T_{mo} \quad (3)$$

This provides the final equation

$$\ln\left(\frac{T_s - T_{mo}}{T_s - T_m}\right) = \left(\frac{\bar{h} \cdot A}{mC_{pm}}\right)t \quad (4)$$

Thus, the Eq. (4) is of the form $y = m \cdot x$

Where y is L.H.S., x is t , and slope m is $\left(\frac{\bar{h}A}{mC_{pm}}\right)$

Hence a plot made with the experimental data between $\ln\left(\frac{T_s - T_{mo}}{T_s - T_m}\right)$ versus t should yield a straight line with a slope $\left(\frac{\bar{h}A}{mC_{pm}}\right)$ from which the average heat transfer coefficient ($\bar{h}$) can be calculated.

Development of empirical correlation

Once $\bar{h}$ has been evaluated, the forced convection heat transfer correlation $Nu = a \cdot Re^b \cdot Pr^n$ can be developed. Since milk temperature (T_m) varies during heat transfer it

is necessary to use bulk mean temperature (T_B), (which is similar to using bulk mean temperature in the design of heat exchangers). The bulk mean temperature in the present study is $T_B = \left(\frac{T_{mo} + T_{mf}}{2}\right)$. The physical properties of milk such as, $\rho_m \mu_m$, c_{pm} , k_m are evaluated at bulk mean temperature. These properties were calculated using the equations given below (Munier et al. 2016)

(1) Heat capacity

$$C_{pm} \left(\frac{J}{kg \cdot K} \right) = 3744.48 + 1.15T + 3.93 \cdot 10^{-3} T^2$$

(Minim et al. 2002)

(2) Density

$$\rho_m \left(\frac{kg}{m^3} \right) = 1042.01 - 0.37T + 3.6 \cdot 10^{-4} \cdot T^2$$

(Minim et al. 2002)

Table 1 Heat transfer coefficients in Baffled and Unbaffled vessels using FBT, IBT, Propeller, Paddle and Empirical Correlation for Cow Milk

Type of vessel	Type of Impellers	N (rpm)	Reynolds number	Experimental $\bar{h}$ $\left(\frac{W}{m^2 \cdot K}\right)$	Theoretical $\bar{h}$ $\left(\frac{W}{m^2 \cdot K}\right)$	% Error	Correlation
Baffled Vessel	Flat Six Blade Turbine impeller	85	1251	540	539.1	− 0.6	$Nu = 4.01 \cdot Re^{0.413} \cdot Pr^{0.33}$
		110	1619	611	599.6	− 1.8	
		130	1914	655	642.5	− 1.9	
		150	2208	680	681.6	0.2	
	Inclined Six Blade Turbine impeller	85	1251	509	506.6	− 0.4	$Nu = 2.0 \cdot Re^{0.502} \cdot Pr^{0.33}$
		110	1619	570	576.6	1.1	
		130	1914	640	627	− 2	
		150	2208	670	673.7	0.5	
	Three blade Propeller impeller	85	1251	552	558.3	− 1.1	$Nu = 5.15 \cdot Re^{0.383} \cdot Pr^{0.33}$
		110	1619	637	616.2	3.2	
		130	1914	679	656.9	3.2	
		150	2208	701	711.3	− 1.4	
	Two Blade Paddle Agitator	50	736	594	593	− 0.2	$Nu = 2.33 \cdot Re^{0.543} \cdot Pr^{0.33}$
		60	883	658	654.4	0.5	
		70	1030	721.5	711.5	− 1.4	
		80	1178	764	765	0.1	
Unbaffled Vessel	Flat Six Blade Turbine impeller with scraper	50	736	721.5	698	− 3.3	$Nu = 10.48 \cdot Re^{0.340} \cdot Pr^{0.33}$
		60	883	733	743	1.3	
		70	1030	777	783	0.7	
		80	1178	849	819	− 1.1	
	Inclined Six Blade Turbine impeller with scraper	50	736	679.2	671	0.3	$Nu = 10.69 \cdot Re^{0.331} \cdot Pr^{0.33}$
		60	883	710	713	0	
		70	1030	750	750	− 1.2	
		80	1178	793.6	784	− 1.8	
	Three Blade Propeller impeller with scraper	50	736	776.7	777.3	0	$Nu = 5.25 \cdot Re^{0.461} \cdot Pr^{0.33}$
		60	883	848.8	845.4	− 0.3	
		70	1030	933.7	907.7	− 2.8	
		80	1178	955	965.3	1	

Table 2 Heat transfer coefficients in Baffled and Unbaffled vessels using FBT, IBT, Propeller, Paddle and Empirical Correlation for Standardised Milk

Type of vessel	Type of impellers	N (rpm)	Reynolds number	Experimental $\bar{h}$ ($\frac{W}{m^2 K}$)	Theoretical $\bar{h}$ ($\frac{W}{m^2 K}$)	% Error	Correlation
Baffled Vessel	Flat Six Blade Turbine impeller	85	1246	495	486.1	− 1.8	$Nu = 4.52 * Re^{0.381} * Pr^{0.33}$
		110	1612	539	536.3	− 0.4	
		130	1905	578	571	− 1.1	
		150	2198	615	603.6	− 1.8	
	Inclined Six Blade Turbine impeller	85	1246	481	471.7	− 1.9	$Nu = 4.71 * Re^{0.371} * Pr^{0.33}$
		110	1612	509.3	519.1	1.8	
		130	1905	552	552.3	0	
		150	2198	594.2	582.4	− 2	
	Three Blade Propeller impeller	85	1251	536	526.7	− 1.7	$Nu = 3.63 * Re^{0.423} * Pr^{0.33}$
		110	1619	578	587.4	1.6	
		130	1914	636.6	630.4	− 0.9	
		150	2208	679	669.7	− 1.3	
	Two Blade Paddle agitator	50	733	624	609.9	− 2.3	$Nu = 8.24 * Re^{0.355} * Pr^{0.33}$
		60	879	650	650.7	0.1	
		70	1026	679	687.3	1.2	
		80	1172	742	720.7	− 3	
Unbaffled Vessel	Flat Six Blade Turbine impeller with Scraper	50	733	552	531.2	− 3.9	$Nu = 0.69 * Re^{0.710} * Pr^{0.33}$
		60	879	594	604.6	1.7	
		70	1026	670	674.5	0.6	
		80	1172	772	741.6	− 4	
	Inclined Six Blade Turbine impeller with scraper	50	733	520	492	− 0.2	$Nu = 0.36 * Re^{0.797} * Pr^{0.33}$
		60	879	560	569	− 0.8	
		70	1026	630	643.3	− 2.3	
		80	1172	764	715.5	0.4	
	Three Blade Propeller impeller with scraper	50	733	580	578.9	− 0.8	$Nu = 1.45 * Re^{0.633} * Pr^{0.33}$
		60	879	660	649.7	− 1.5	
		70	1026	735	716	− 2.6	
		80	1172	777	779.5	0.3	

(3) Viscosity

$$\mu_m(C_p) = (0.9565 - 1.3004 * 10^{-3} * T + 1.9580 * 10^{-4} * T^2) + X_F(0.4766 - 1.144 * 10^{-2}T + 7.2642 * 10^{-5}T^2)$$

(Kessler 2002)

(4) Thermal conductivity

$$k_m\left(\frac{W}{m K}\right) = 1.63 * 10^{-2} + 1.4 * 10^{-3}T + 0.2X_w + 4 * 10^{-2}X_F$$

(Kessler 2002)

Results and discussion

The experimental data for Cow Milk (3.5%), Standardised Milk (4.5%) and Full Cream Milk (6%) are presented in Tables 1, 2 and 3. Each table in turn shows the data for (A) Baffled Vessel and (B) Unbaffled Vessel (with scraper). Under each category the data for N (rpm), Reynolds number (Re), experimentally determined heat transfer coefficient ($\bar{h}$) and theoretical heat transfer coefficient ($\bar{h}$) computed using empirical correlation are presented.

It could be seen that as N increases the $\bar{h}$ also increases with each impeller in all three types of milk. This is understandable since flow velocities increase with increase in N thereby increasing the rate of heat transfer.

Table 3 Heat transfer coefficients in Baffled and Unbaffled vessels using FBT, IBT, Propeller, Paddle and Empirical Correlation for Full Cream milk

Type of vessel	Type of impellers	N (rpm)	Reynolds number	Experimental $\bar{h}$ ($\frac{W}{m^2 K}$)	Theoretical $\bar{h}$ ($\frac{W}{m^2 K}$)	% Error	Correlation
Baffled vessel	Flat Six Blade Turbine impeller	85	1237	424	429.5	1.2	$Nu = 0.86 * Re^{0.596} * Pr^{0.33}$
		110	1609	515	500.9	− 2.8	
		130	1892	572	553.3	− 3.3	
		150	2184	588	602.6	2.4	
	Inclined Six Blade Turbine impeller	85	1237	414	421.3	1.7	$Nu = 0.85 * Re^{0.594} * Pr^{0.33}$
		110	1609	503	496.6	− 3.7	
		130	1892	560	552.3	− 3.5	
		150	2184	573	605	2.8	
	Three Blade Propeller impeller	85	1237	568.7	566.8	0.3	$Nu = 11.24 * Re^{0.274} * Pr^{0.33}$
		110	1609	617.5	608.2	1.5	
		130	1892	636.6	636.6	0	
		150	2184	679	673.9	0.7	
	Two Blade Paddle agitator	50	728	594.2	575.5	− 3.2	$Nu = 2.71 * Re^{0.514} * Pr^{0.33}$
		60	873.4	636	632	− 0.6	
		70	1019	679	684.2	0.7	
		80	1164.5	763	732.8	− 4.1	
Unbaffled vessel	Flat Six Blade Turbine impeller with Scraper	50	728	552	538.6	− 2.4	$Nu = 0.698 * Re^{0.710} * Pr^{0.33}$
		60	873.4	594	613.1	3.1	
		70	1019	670	684	2	
		80	1164.5	772	752	− 2.6	
	Inclined Six Blade Turbine impeller with Scraper	50	728	520	493	− 5.4	$Nu = 0.36 * Re^{0.797} * Pr^{0.33}$
		60	873.4	560	570	1.7	
		70	1019	630	644.5	2.2	
		80	1164.5	764	716	− 6.5	
	Three Blade Propeller impeller with Scraper	50	728	580	580.7	0.1	$Nu = 1.27 * Re^{0.633} * Pr^{0.33}$
		60	873.4	660	651.8	− 1.2	
		70	1019	735	718.6	− 2.2	
		80	1164.5	777	782	0.6	

Baffled vessel-A

In baffled vessel, the data obtained with Paddle agitator indicates the highest heat transfer coefficient ($\bar{h}$) in spite of lower N and lower Reynolds number. This is closely followed by Three Blade Propeller impeller, Flat Six Blade Turbine (FBT) and Inclined Six Blade Turbine (IBT). The Two Blade Paddle agitator designed with large $D_a : D_t$ ratio appears to generate highest volumetric liquid circulation in all three types of milk, thereby resulting in highest heat transfer coefficient ($\bar{h}$). Amongst the three impellers viz, Propeller, FBT and IBT having the same $D_a : D_t$ ratio of 1:3, the performance of the Propeller impeller is the best. This could be attributed to the axial flow currents that

travel vertically down to the bottom and to the top of surface transferring the heat in a cyclic manner. FBT provides the second best performance, due to radial flow currents that split and partly flow down along the heat transfer surface. It is inferred that IBT by its inherent design provides vectoral combination of vertical and radial flow currents thereby impeding good circulation resulting in stagnant zones and low $\bar{h}$.

Unbaffled vessel-B

In unbaffled vessel the effect of scraping the heat transfer area, results in higher $\bar{h}$ values than that of baffled vessel. Propeller impeller exhibits better $\bar{h}$, followed by FBT and

Fig. 3 Comparative performance of the impellers in baffled vessel and unbaffled vessel with scraper for cow milk, standardised milk and cream milk. **a** Baffled vessel, **b** Unbaffled vessel

IBT, in spite of lower rpm than that of the baffled vessel. This may be a pointer to the fact that milk components that have a tendency to form a film adhering to heat transfer area need to be wiped for better heat transfer coefficient ($\bar{h}$).

Development of empirical correlation

The empirical correlation developed for each type of milk heated in the baffled and unbaffled vessels using different types of impellers are also shown in the tables. The correlation $Nu = a \cdot Re^b \cdot Pr^n$ described elsewhere was substituted with $n = 0.33$ and by linear regression for $\ln \left(\frac{Nu}{Pr^{0.33}} \right) = \ln a + b \ln Re$ from which a and b could be determined.

The percentage error calculated between Experimental $\bar{h}$ and Theoretical $\bar{h}$ data is less than $\pm 10\%$ indicating a good correlation between the Theoretical versus Experimental $\bar{h}$ values. Hence the correlations depicted in the tables can be used for theoretical evaluation of $\bar{h}$ for all the three types of milk in agitated vessels using a specific

impeller. The theoretical $\bar{h}$ values can therefore be used to evaluate the overall heat transfer coefficient while designing heat transfer area in agitated vessels.

Figure 3 A depicts a comparative performance of impellers in Baffled Vessel, indicating experimental values of $\bar{h}$ for the three types of milk and Fig. 3 B shows the performance in Unbaffled Vessel with scraping provision.

These figures show a decreasing trend in $\bar{h}$ from Cow Milk to Standardised Milk to Full Cream Milk for each impeller both in Baffled and Unbaffled Vessels. This could be attributed to increasing fat and SNF contents forming films on heat transfer area, resulting in increased thermal resistance.

Conclusion

Forced convection heat transfer coefficients for milk with varying Fat and SNF contents using mechanical agitators in Baffled and Unbaffled vessels have been determined. Among the impellers the highest $\bar{h}$ values were observed

with Two Bladed Paddle agitator in Baffled vessel. Increased fat and SNF content in milk resulted in lower Re for the same rpm due to increase in viscosity giving low $\bar{h}$ values.

The present investigation was carried out with different milks using four types of impellers to investigate the forced convection heat transfer coefficient ($\bar{h}$). Empirical correlation has been developed for each impeller for cow milk, standardised milk and full cream milk. These correlations would be useful in theoretical estimation of $\bar{h}$ required for determining overall heat transfer coefficient while designing the heat transfer area in agitated vessels, particularly with respect to varied combinations of milks (fat and SNF).

The study thus provides a scientific basis for the pre-heat treatment of milk with potential to scale up for industrial applications. Similarly, different liquid versus impeller combinations could be investigated to find out the $\bar{h}$. Also, the experimental data thus obtained could be correlated with Computational Fluid Dynamics Analysis (CFD).

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